



(12) **United States Patent**
Chi et al.

(10) **Patent No.:** **US 9,209,079 B2**
(45) **Date of Patent:** **Dec. 8, 2015**

(54) **CONDUCTOR LAYOUT TECHNIQUE TO
REDUCE STRESS-INDUCED VOID
FORMATIONS**

(71) Applicant: **Taiwan Semiconductor Manufacturing
Co., Ltd.**, Hsin-Chu (TW)

(72) Inventors: **Min-Hwa Chi**, Hsin-Chu (TW);
Tai-Chun Huang, Hsin-Chu (TW);
Chih-Hsiang Yao, Hsin-Chu (TW)

(73) Assignee: **Taiwan Semiconductor Manufacturing
Co., Ltd.**, Hsin-Chu (TW)

(*) Notice: Subject to any disclaimer, the term of this
patent is extended or adjusted under 35
U.S.C. 154(b) by 5 days.

(21) Appl. No.: **14/486,012**

(22) Filed: **Sep. 15, 2014**

(65) **Prior Publication Data**

US 2015/0011086 A1 Jan. 8, 2015

Related U.S. Application Data

(60) Division of application No. 13/869,844, filed on Apr.
24, 2013, now Pat. No. 8,836,141, which is a
continuation of application No. 11/438,127, filed on
May 22, 2006, now Pat. No. 8,435,802.

(51) **Int. Cl.**
H01L 21/44 (2006.01)
H01L 21/768 (2006.01)
H01L 23/528 (2006.01)
H01L 23/532 (2006.01)

(52) **U.S. Cl.**
CPC **H01L 21/76898** (2013.01); **H01L 21/768**
(2013.01); **H01L 23/528** (2013.01); **H01L**
23/53228 (2013.01)

(58) **Field of Classification Search**

CPC H01L 21/768; H01L 21/76898; H01L
23/528; H01L 23/53228

USPC 438/5, 622, 638, 637, 624, 618, 667;
257/773, 774

See application file for complete search history.

(56) **References Cited**

U.S. PATENT DOCUMENTS

2,175,036 A * 10/1939 Sipe 174/84 S
5,317,185 A 5/1994 Fernandes et al.
5,686,356 A 11/1997 Jain et al.
5,814,557 A 9/1998 Venkatraman et al.

(Continued)

FOREIGN PATENT DOCUMENTS

NP 2087-TW A 10/1999

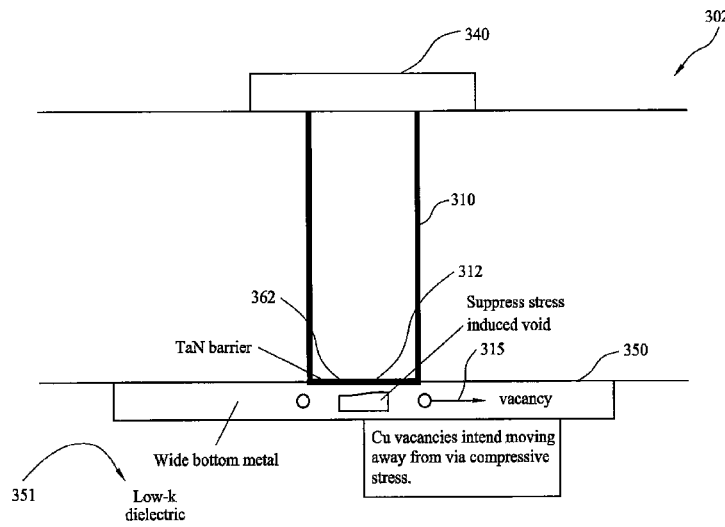
Primary Examiner — Mohammed Shamsuzzaman

(74) *Attorney, Agent, or Firm* — Duane Morris LLP

(57) **ABSTRACT**

A semiconductor device is prepared by an annealing process to interconnect at least two components of the device by a conductor line surrounded by an insulator material. The annealing process results in formation of residual stresses within the conductor line and the insulator material. One or multiple notches are designed in the layout on a selective portion of the mask for patterning conductor line. The existence of the notch or notches on the selective portion generates extra stress components within the conductor line than would exist without the existence of the notch. The position of the notch is selected so that the extra stress components substantially counteract the residual stresses, thereby causing a net reduction in the residual stresses. The reduction in the residual stresses results in a corresponding mechanical stress migration and therefore improvement in the reliability of the device.

13 Claims, 15 Drawing Sheets



(56)

References Cited

U.S. PATENT DOCUMENTS

6,081,031	A	6/2000	Letterman, Jr. et al.
6,081,036	A *	6/2000	Hirano et al. 257/773
6,670,216	B2 *	12/2003	Strauch 438/106
6,917,116	B2	7/2005	Kordic et al.
7,033,924	B2	4/2006	Ogawa et al.
2002/0192886	A1	12/2002	Inoue
2003/0122260	A1	7/2003	Ogawa et al.
2004/0041274	A1	3/2004	Ogawa et al.

2004/0140565	A1	7/2004	Kordic et al.
2005/0095845	A1	5/2005	Kawano
2005/0107870	A1	5/2005	Wang et al.
2005/0186782	A1 *	8/2005	Burke et al. 438/638
2005/0260850	A1	11/2005	Loke et al.
2007/0018299	A1	1/2007	Koo et al.
2007/0259518	A1 *	11/2007	Allman et al. 438/622
2010/0155862	A1	6/2010	Shiraishi et al.
2010/0258309	A1	10/2010	Ayodele et al.
2010/0330798	A1	12/2010	Huang et al.

* cited by examiner

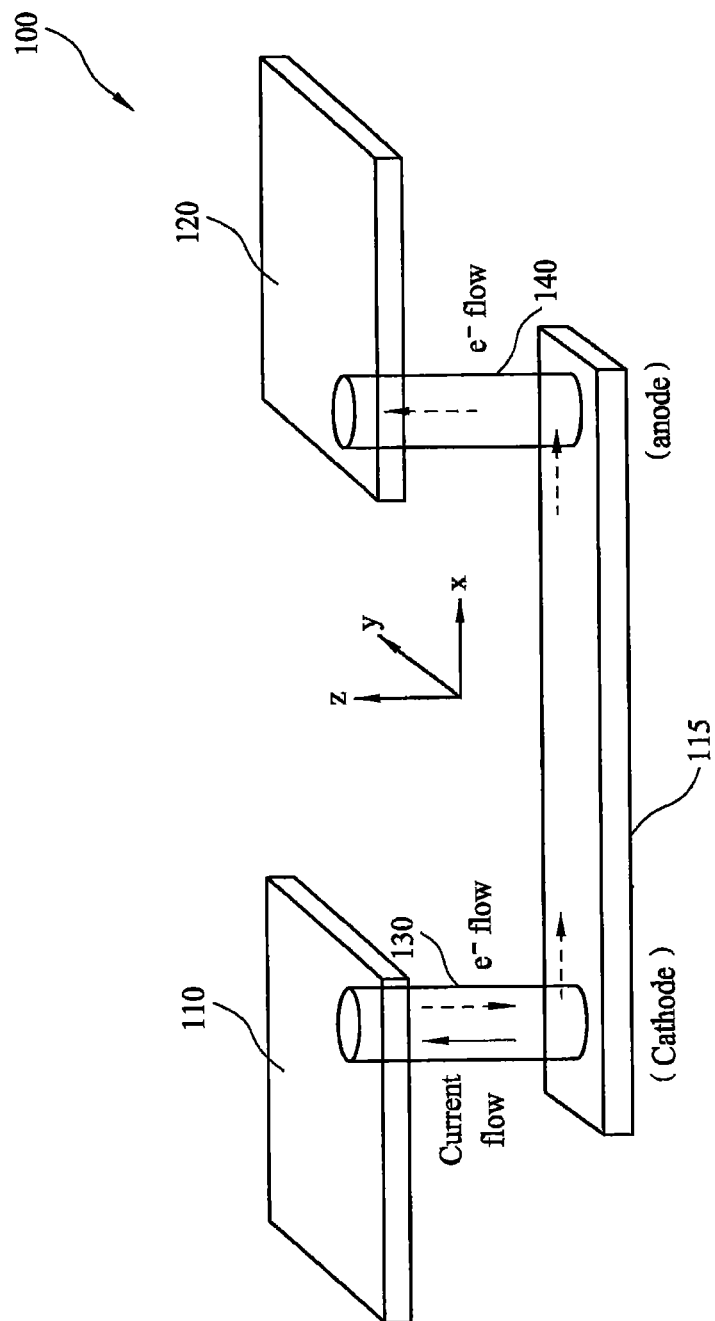


FIG. 1A
(PRIOR ART)

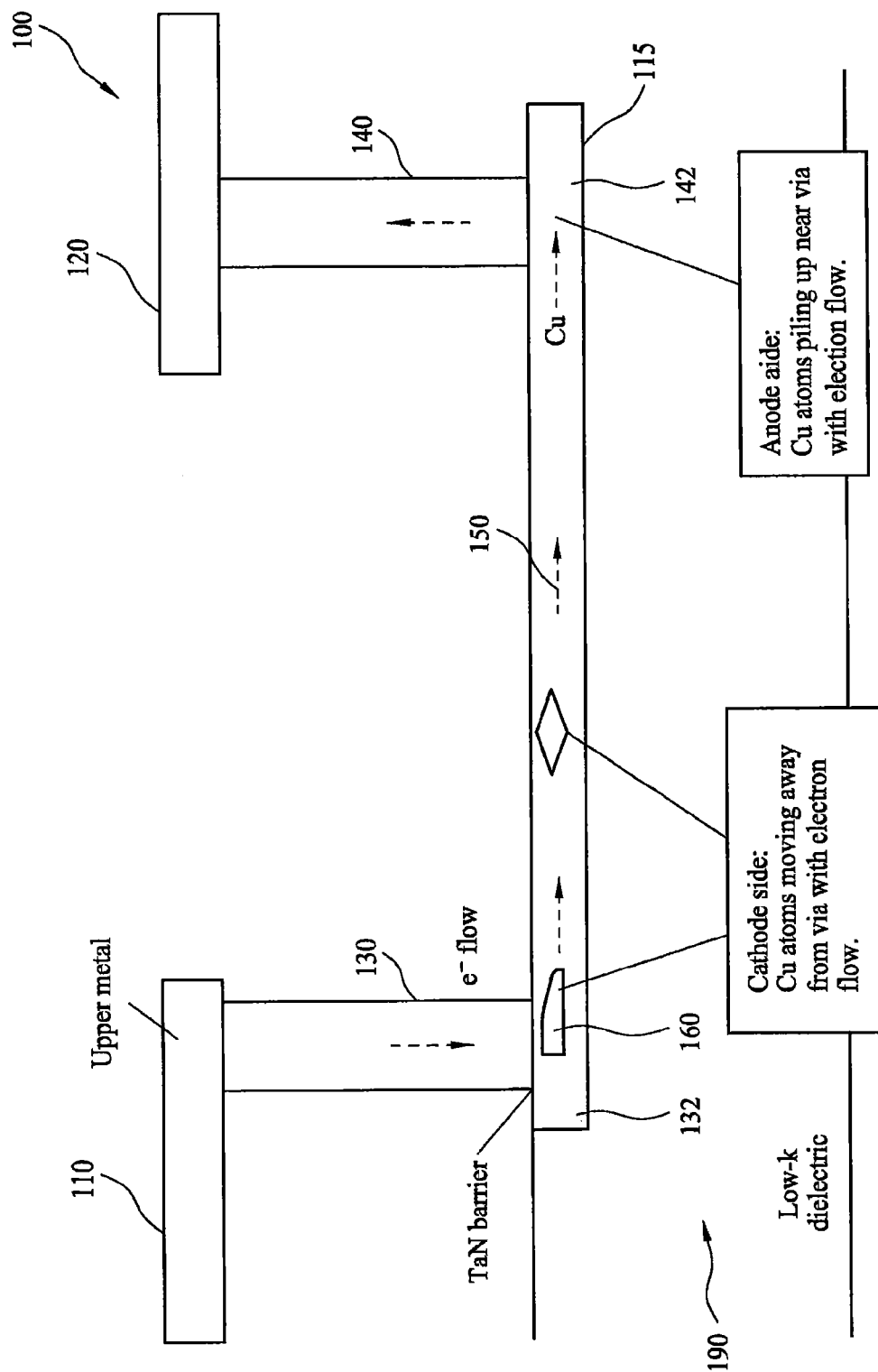


FIG. 1B
(PRIOR ART)

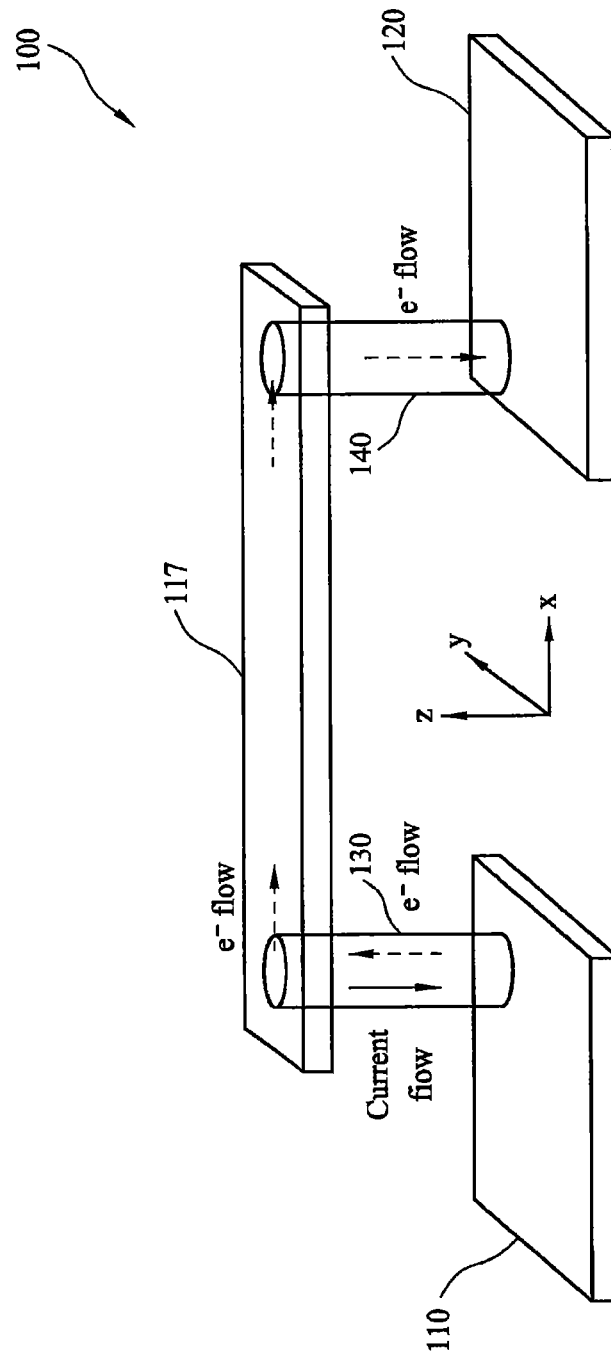


FIG. 1C
(PRIOR ART)

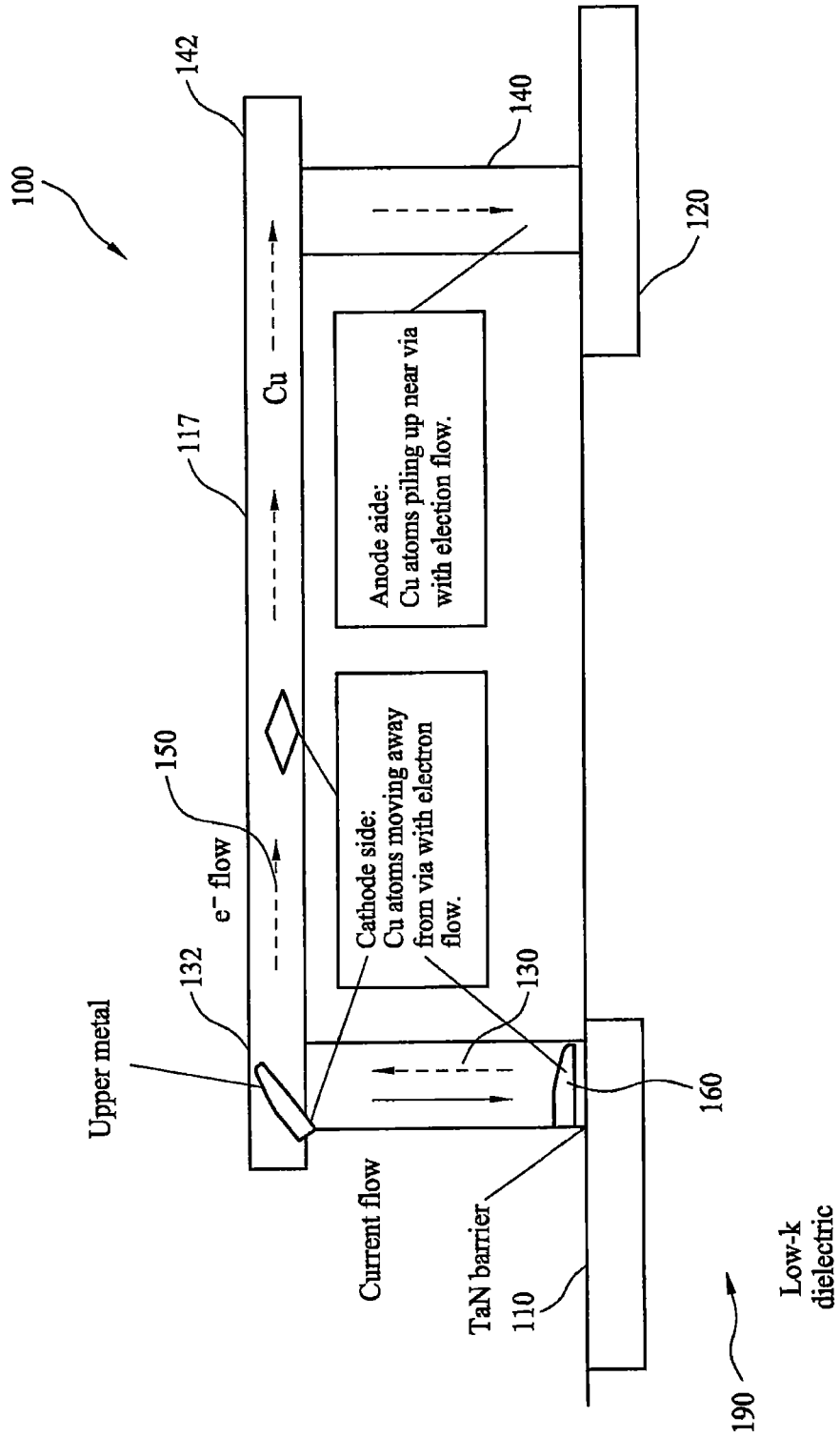


FIG. 1D
(PRIOR ART)

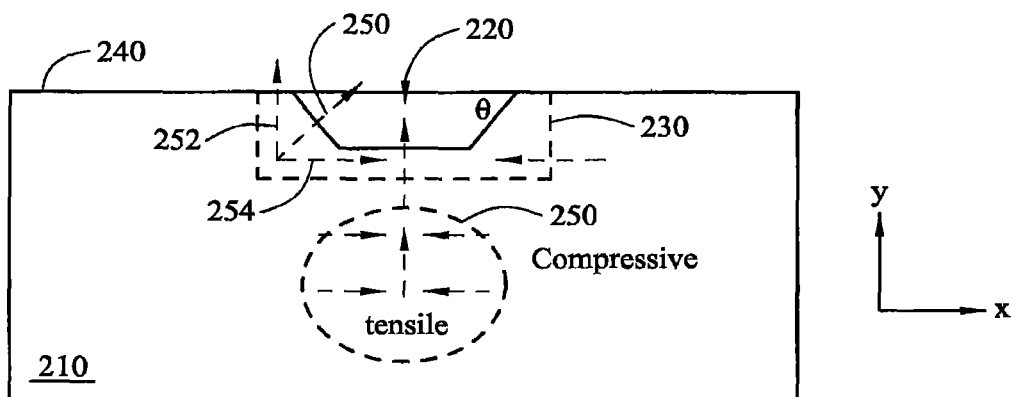


FIG. 2A

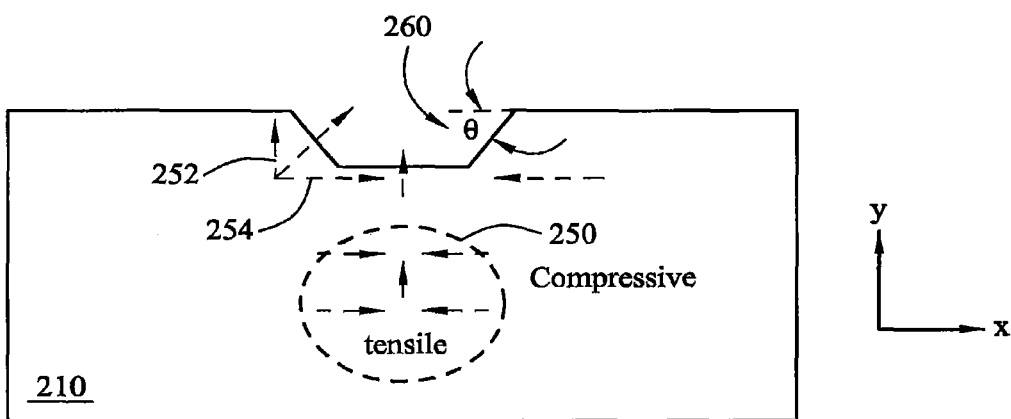


FIG. 2B

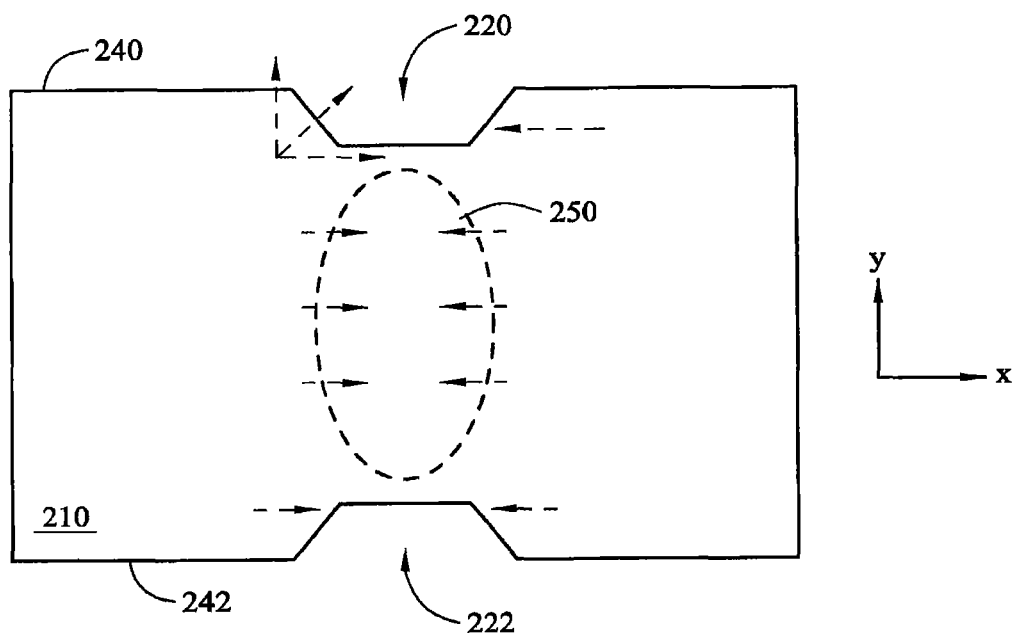


FIG. 2C

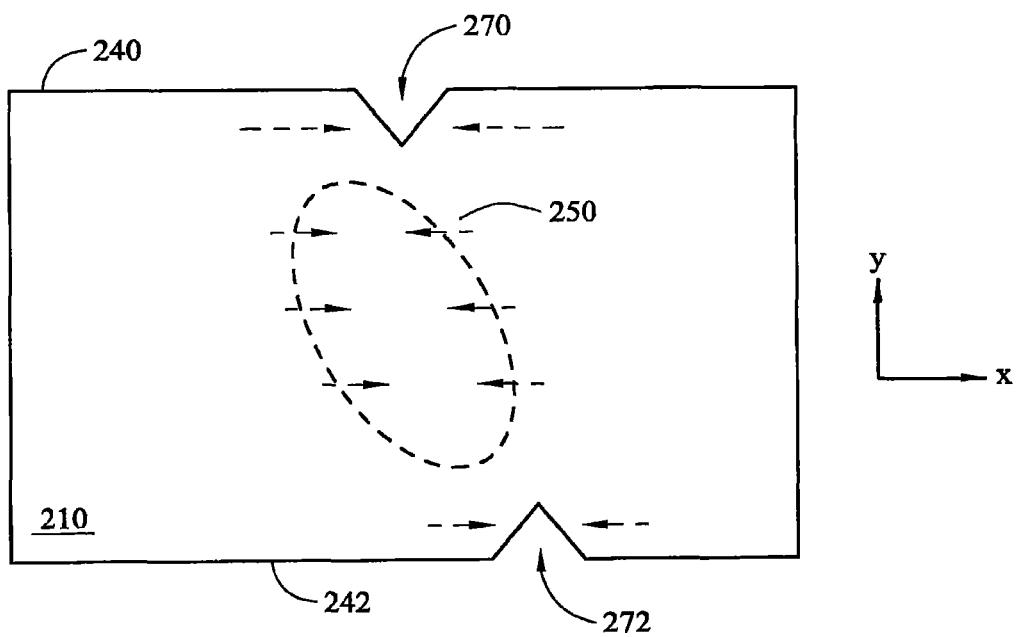


FIG. 2D

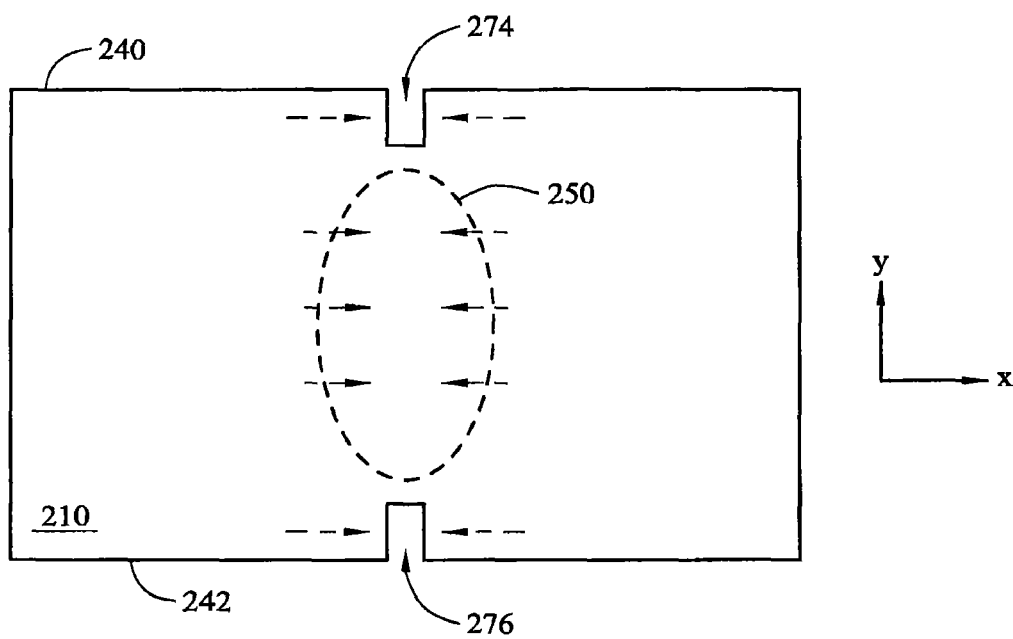


FIG. 2E

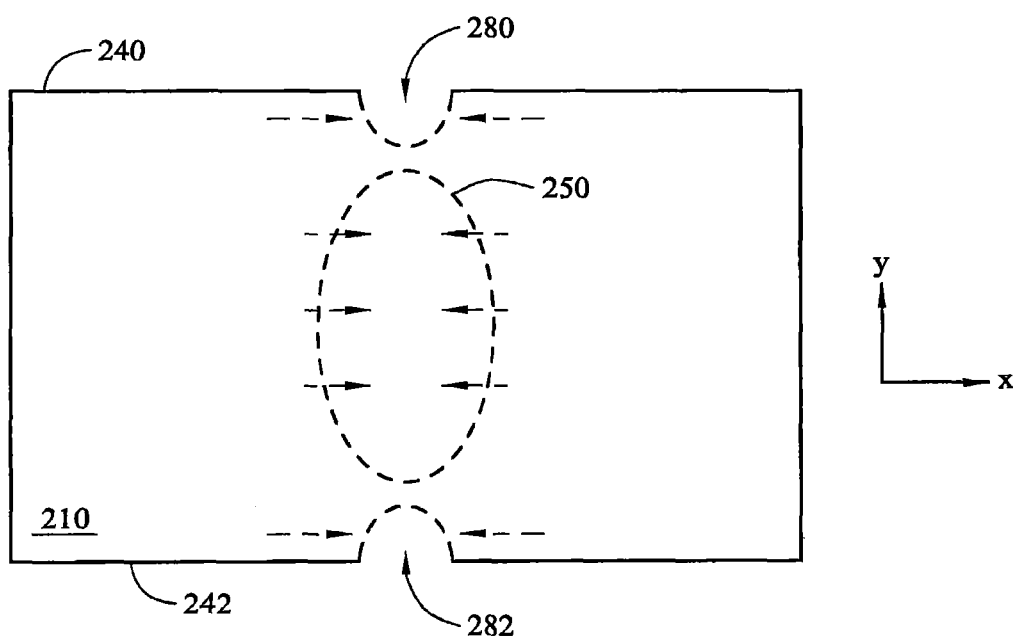


FIG. 2F

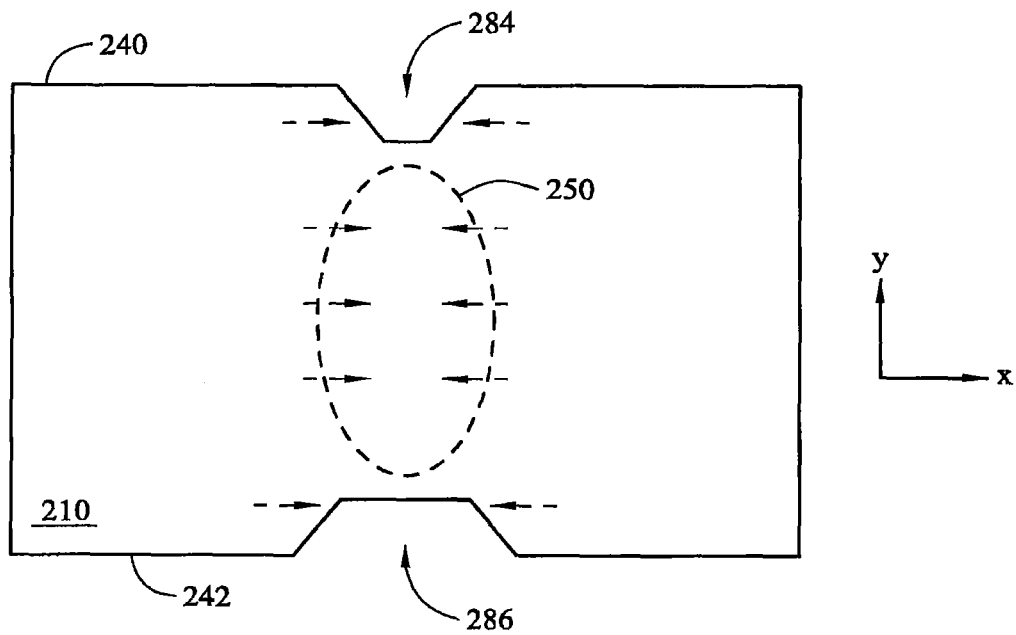


FIG. 2G

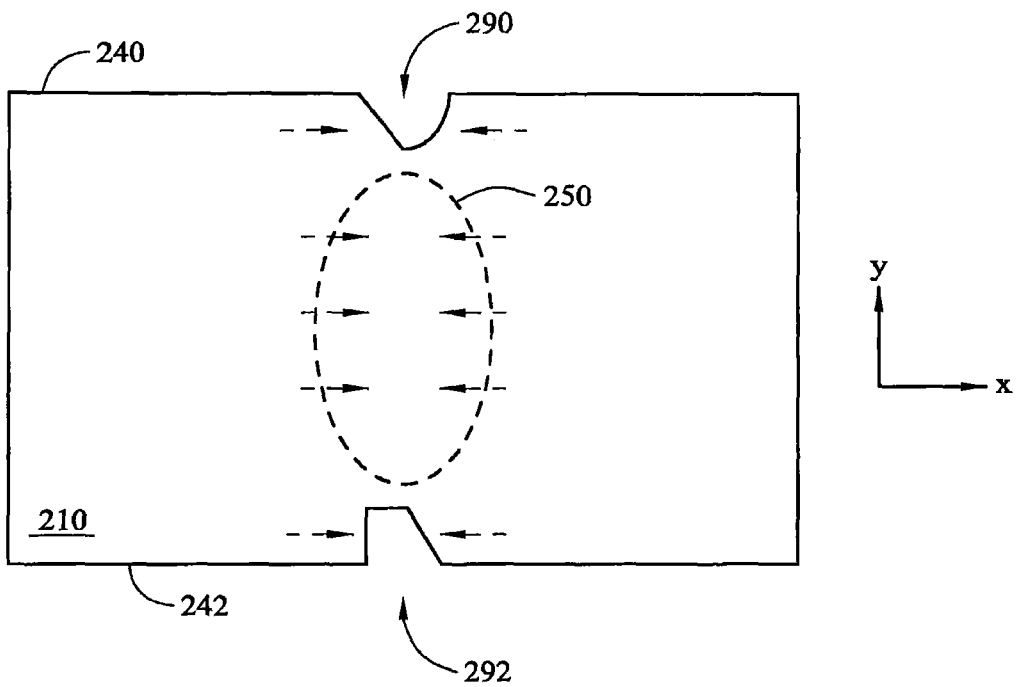


FIG. 2H

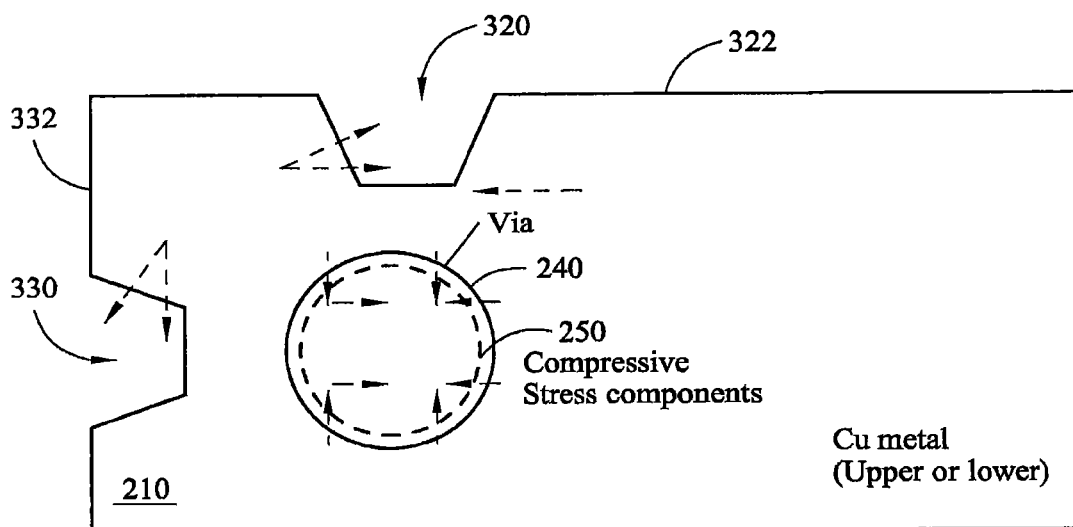


FIG. 3A1

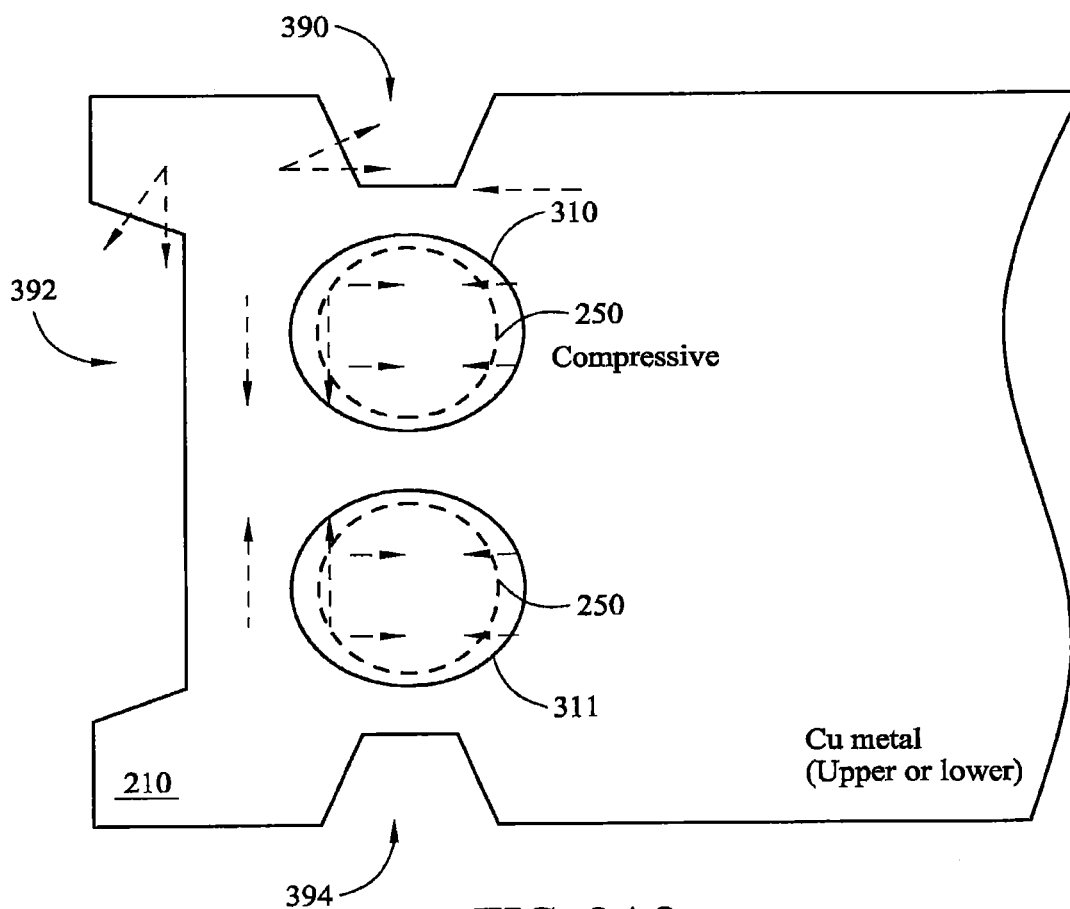


FIG. 3A2

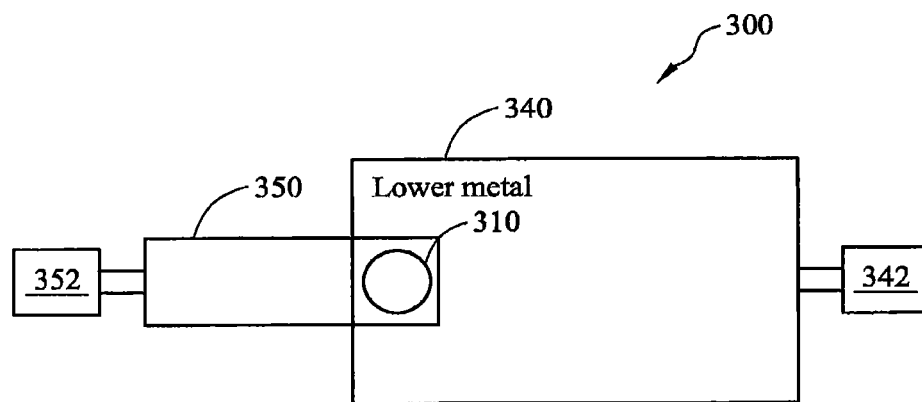


FIG. 3B

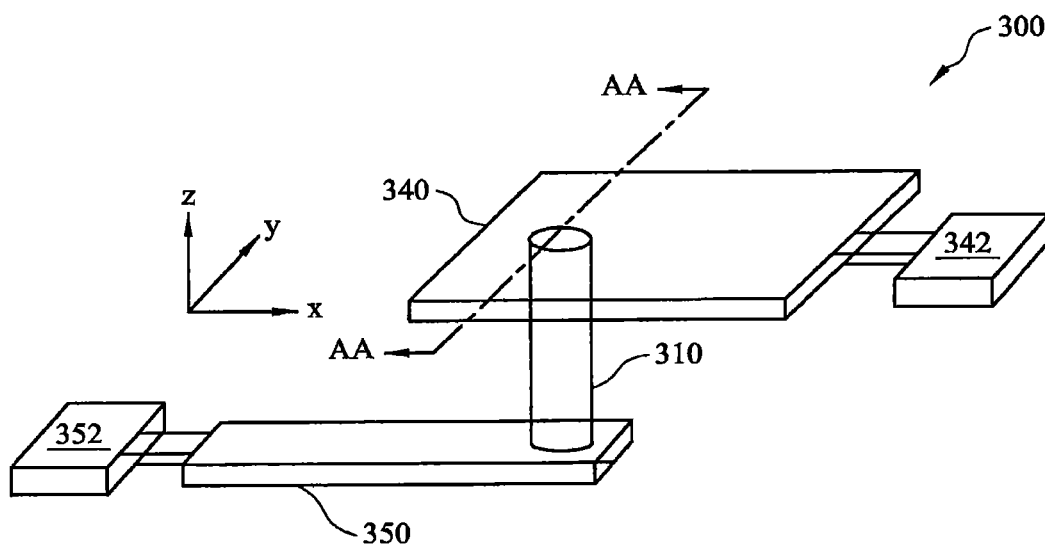


FIG. 3C

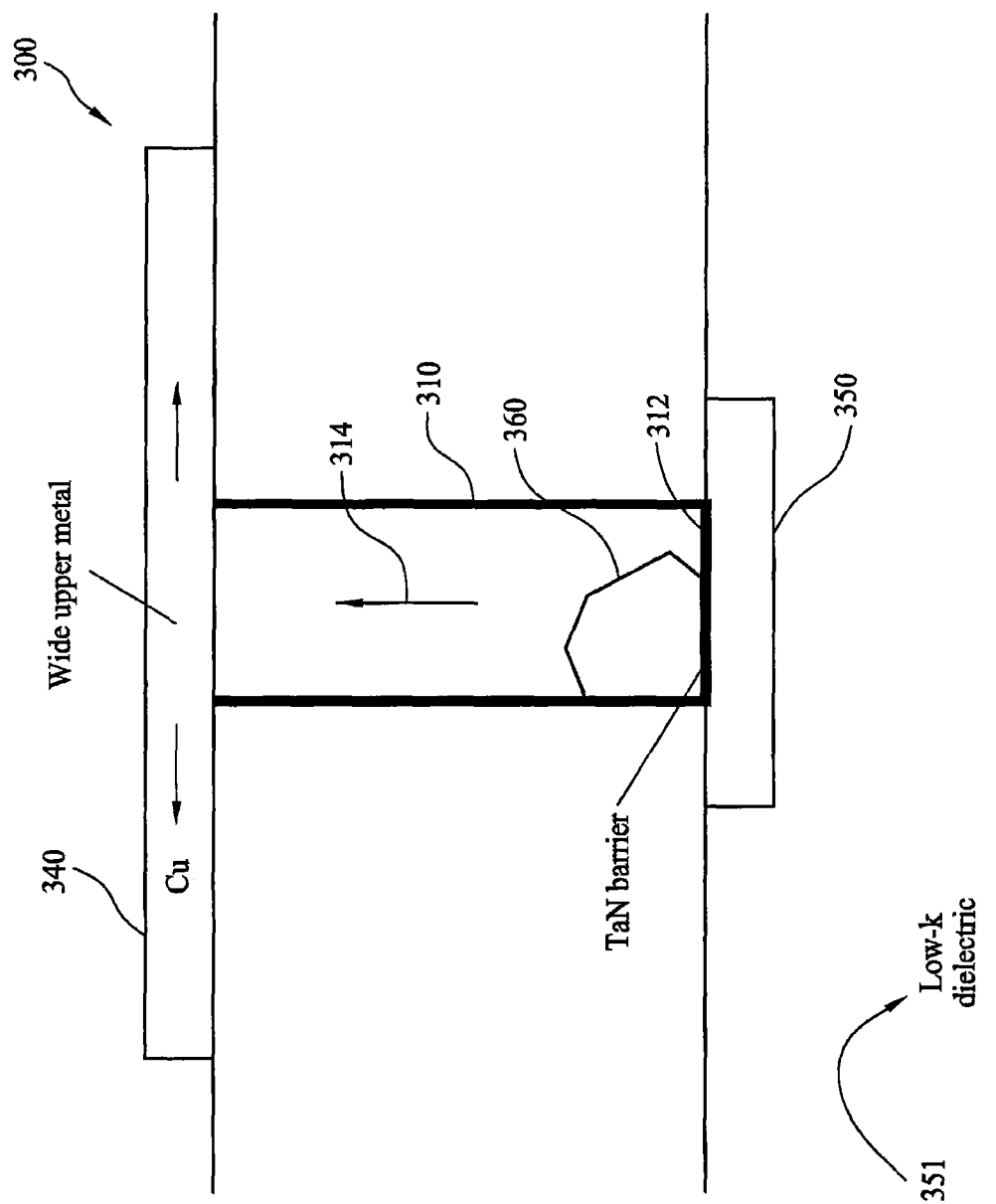


FIG. 3D

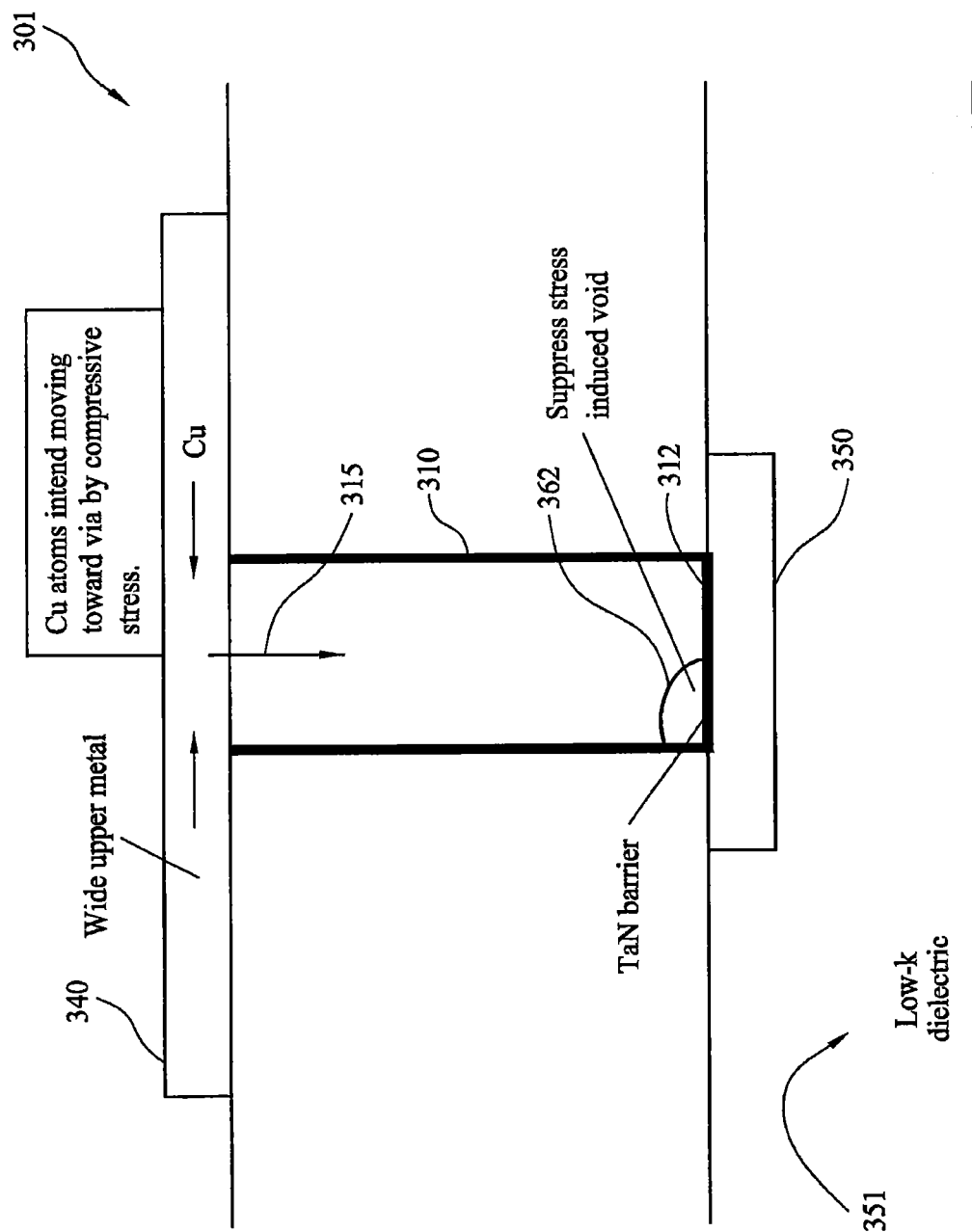


FIG. 3E

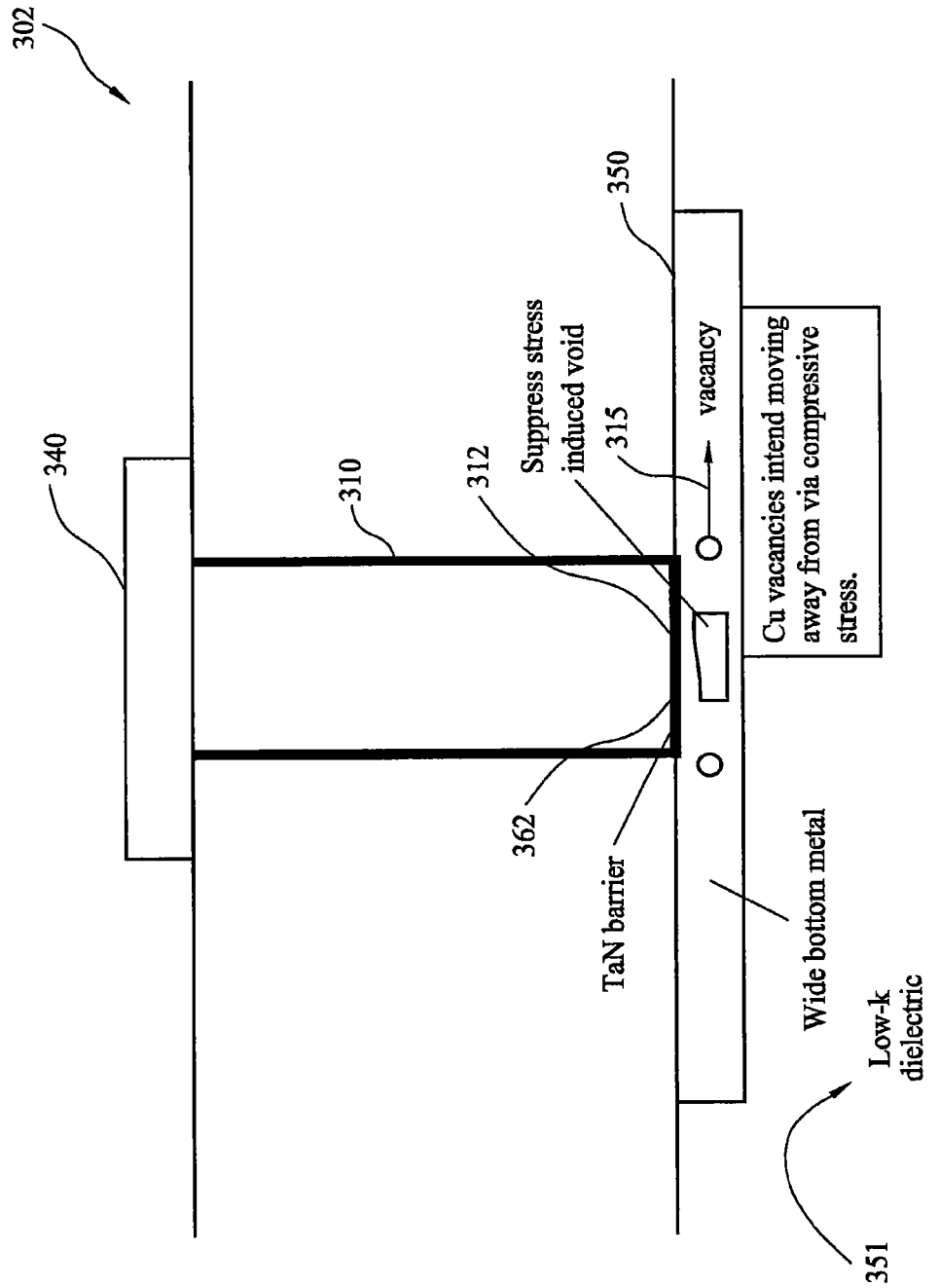


FIG. 3F

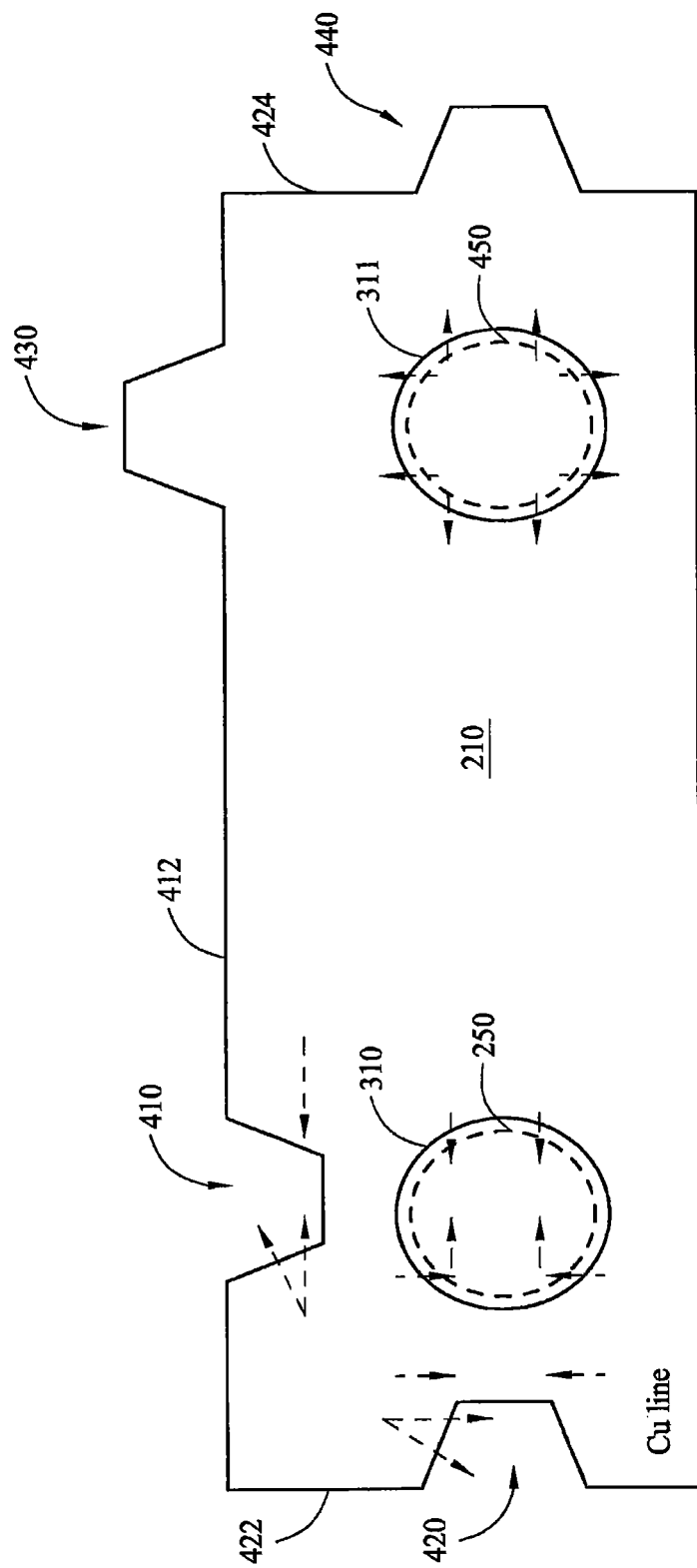


FIG. 4

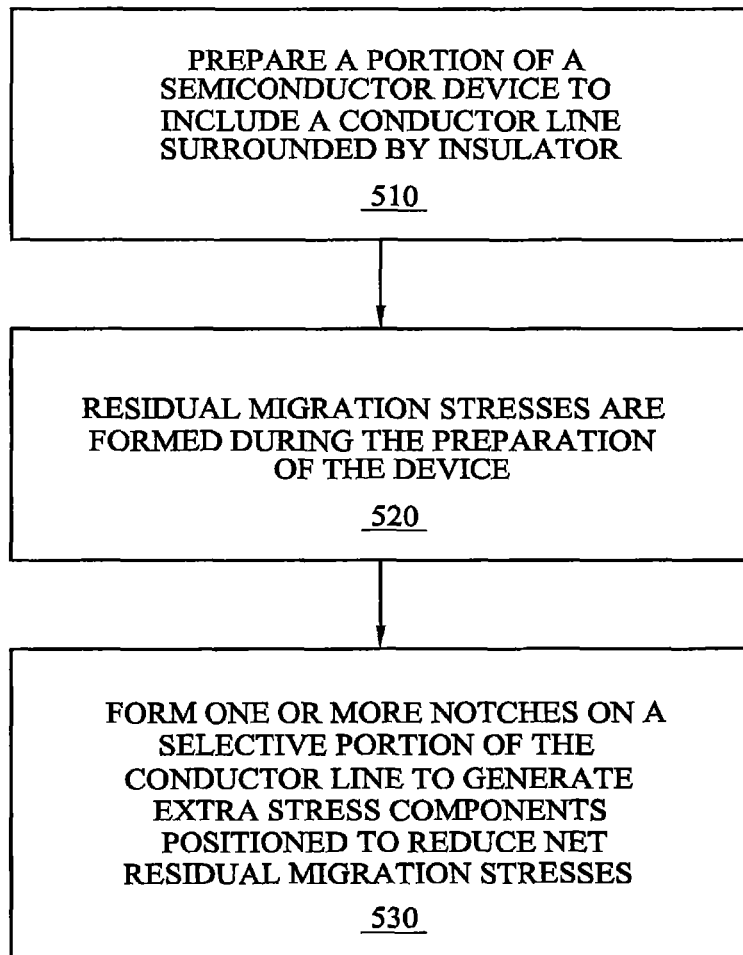


FIG. 5

CONDUCTOR LAYOUT TECHNIQUE TO REDUCE STRESS-INDUCED VOID FORMATIONS

RELATED APPLICATIONS

This application is a divisional of U.S. patent application Ser. No. 13/869,844, filed on Apr. 24, 2013, which is a continuation of U.S. patent application Ser. No. 11/438,127, filed on May 22, 2006 and issued as U.S. Pat. No. 8,435,802 on May 7, 2013, the contents of each of which are hereby incorporated by reference as if set forth in their entireties.

BACKGROUND

The present invention relates generally to semiconductor integrated circuits, and, more particularly, to a method and apparatus for reducing void formation induced failures caused as a result of stress-migration characteristics of conductors in integrated circuits.

Since the introduction of integrated circuit (IC) devices, there has been a continuous drive to improve their quality, reliability and cost/unit. This drive has been fueled by consumer demand for improved computers and electronic devices, which are more reliable, cost less, occupy less space and use less power.

In a semiconductor fabrication process, IC's are fabricated by sequentially forming features in layers of material in a bottom-up manufacturing method. The manufacturing process utilizes a wide variety of processing and measuring tools and techniques to form various layered features.

Reliability is a significant factor in IC design, production and operation. Process parameters are tightly controlled to ensure high reliability during all stages of manufacturing process. Where feasible, samples are taken and tests are performed at many intermediate stages of the process so corrective action may be taken if found to be necessary. The importance of precise control of process parameters such as thickness, dopant concentration, gate length and temperatures will be appreciated when it is realized that IC manufacturing typically requires precise execution of hundreds of steps. Completion of all steps for each wafer may typically require several days or even weeks. An improvement in the reliability of the circuit design itself and in the manufacturing process is important to avoid a significant economic loss of wafers themselves and in lost opportunity to meet customer demand. Various factors affecting reliability of a semiconductor device are described in FIGS. 1A through 1D below.

FIGS. 1A, 1B, 1C and 1D are illustrative diagrams of interconnect structure between two adjacent layers of interconnection in a state-of-art IC with multiple layers of interconnection (not shown) according to prior art. FIGS. 1A and 1C are views in perspective illustrating the interconnect structure and FIGS. 1B and 1D are cross sectional views of the interconnect structure. Referring to FIGS. 1A and 1B, conductors 110, 115, and 120 are connected through vias 130 and 140 or through holes. The lower metal line 115 is narrower compared to the other metal lines 110 and 120. Hence, if there is a current flowing from metal 120 through via 140, metal line 115, via 130, and metal 110 as shown in FIG. 1A with the electron current flowing in the opposite direction of current flow, the narrower metal line 115 carries a higher current density than metal lines 110 and 120. A low k dielectric 190 is used as insulator. Similarly, in FIGS. 1C and 1D, conductors 110, 117, and 120 are connected through vias 130 and 140. The upper metal line 117 is narrower compared to the other metal lines 110 and 120. The low k dielectric 190 is used

as insulator. The conducting materials of metal lines and vias typically used in CMOS technology include aluminum, aluminum alloys, refractory metal, copper, copper alloys, gold, gold alloys, silver, silver alloys, and the like, and doped polysilicon and silicides.

Typical examples of various components interconnected by metal lines and vias within an IC include transistors, diodes, resistors, capacitors, contact terminals and the like. Advances in sub-micron CMOS technology generally requires that the interconnect density be enhanced by decreasing the metal pitch and via size as well as increasing the number of interconnect metal layers. Therefore, as the dimensions of the active devices decreases and interconnect density increases, there is typically higher current density flowing in metal lines and vias. The increased time constant and reduced reliability of multi-level interconnection are considered major possible limitations to the circuit performance.

One factor affecting reliability of IC is the mechanical stress migration of metal lines and vias. As is well known, the mechanical stress migration is the movement of atoms of the conducting material from which the conductor is fabricated as a result of residual stress caused by the mismatch of thermal expansion coefficients between the metal and surrounding dielectric materials. The residual stress is typically tensile as the thermal expansion coefficients of usual conduction materials are typically larger than that of the surrounding insulator. The magnitude of tensile stress in metal lines is bi-axial and larger with wider dimension. Further, the mechanical stress migration occurs most significantly at elevated temperatures (e.g. -100-200° C.). At such temperature range, the atomic movement in metal line is more significant due to atoms energetic enough under large enough mechanical stress. There is no significant atomic movement either at too high a temperature e.g. >300° C. (due to much reduced residual mechanical stress in metal line) or at room temperature due to not enough energy of atoms.

Another factor affecting reliability of IC is the electro-migration, which is known as the migration of metal atoms e.g. copper atoms in a conductor along the direction of electron flow (or to the opposite direction of electrical current flow as defined conventionally). The migration of metal atoms will occur more significantly on locations where there is larger electron current density e.g. locations of metal line near corners, inside vias near bottom and locations at elevated temperatures e.g. due to local excessive thermal generation by current paths. Both the mechanical stress migration and electro-migration results in damage in terms of void formations and formation of hillock growths or accumulations that enlarge over time. These voids will eventually leads to circuit failures by open or high resistive metal lines or vias. These hillocks will eventually leads to circuit failures by shorts or lower breakdown voltage in between metal layers. Even when there are no substantial mechanical stresses present, electro-migration may still occur provided there is a large enough current density flowing at high enough operating temperature e.g. 80-150° C. Similarly, even when there is no current flow, mechanical stress migration can also occur provided there is large enough mechanical stress at high enough operation temperature. Thus, the mechanical stress migration and electro-migration are two independent failure mechanisms of multi-level inter-connection in modern VLSI; however, these two mechanisms may work collectively together for accelerating void formation, or they may influence each other for suppressing the net atomic migration depending on the electron flow direction. Some techniques for minimizing

mechanical stress migration may also reduce electro-migration and improve reliability of multi-level inter-connection in VLSI.

Referring to FIG. 1B, voids or void formation **160** may be formed adjacent to via bottom below the barrier metal of via on the cathode side **132** e.g., via **130** bottom by electro-migration of copper atoms along electron flow **150**, and copper accumulation occurs at the anode side **142** e.g., via **140**. The mechanism of void formation by electro-migration is thus related to the movement of copper atoms away from the via bottom **132** along the direction of electron flow **150** or alternatively copper vacancies moving towards the via bottom along the direction of current flow.

As described earlier, voids may also be formed due to mechanical stress migration, when there is no current flowing through metal lines and vias (i.e. there is no electro-migration in this case). In a via structure with wide upper metal, similar to FIG. 1B, void may be formed above the barrier metal near via **130** or **140** bottom not shown in FIG. 1B as a result of larger tensile stress in the wider metal lines **110** and **120** than the stress in narrower metal line **115** and the inside of vias **130** and **140**. Thus, there is a net mechanical stress encouraging Cu atoms movement toward the upper wide metal line **110** and **120** with void formed above the via bottom. Note that the barrier metal between the metal line **115** and the bottom of via **130**, **140** prevents those Cu atoms moving toward the upper wide metal line **110** through the barrier from the narrow metal line **115**; as a result, the void by mechanical stress migration in this structure is typically formed above the barrier near via bottom. Certainly, as described earlier, both mechanical stress migration as well as electro-migration can result in formation of voids in a collective manner.

Now referring to FIG. 1D, the narrower upper metal line **117** carries higher current density than the wider metal line **110**, **120** and it is similar to metal line **115**. Voids **160** are formed in via **130** bottom above the barrier metal and copper line corner at cathode side **132** along the direction of electron flow by electro-migration mechanism. In the via structure with wide lower metal, similar to FIG. 1B, stress induced voids may be formed below barrier metal near via **130** as a result of mechanical stress migration by the larger magnitude of tensile stress in wider metal line **110** or **120**.

As described earlier, void formation, such as the formation of void **160**, is generally associated with tensile stresses in metal line. However, those atoms moving from voids will finally accumulate elsewhere nearby and form hillocks. The local area near hillocks in metal line generally has less tensile stress or even compressive stresses. The void formations result in an increased resistance and may eventually cause an open circuit failure in the interconnect. The accumulation (or hillocks) results in fracturing the surrounding passivation layers and may produce short circuits between neighboring interconnects. Obviously, both void formation and accumulation negatively impacts chip reliability.

The IC interconnects have been traditionally made from aluminum and its alloys. However, in recent years, the use of copper and copper alloys in combination with materials of lower dielectric constant as insulators has increased due to lower resistance (compared to aluminum) and reduced capacitance values for the interconnects. However, because copper is not easily etched it requires new processing methods, notably the damascene process with chemical-mechanical polishing (CMP).

The following technical publications describe various aspects of reducing mechanical stress induced voiding [1-3]

and electro-migration induced voiding [4-5] in copper interconnects to improve reliability and are incorporated herein by reference:

- a. K. Y. Y. Doong, and et al., stress induced voiding and its geometry dependency characterization, IEEE International Reliability Physics Symposium, p. 138, 2003.
- b. I. Oshima, et al., Suppression of stress-induced voiding in Copper interconnects, Technical Digest of IEDM, p. 757, 2003.
- c. E. I. Ogawa, et al., Stress induced voiding under vias connected to wide Cu metal leads. IEEE International Reliability Physics Symposium, p. 312-321, 2002.

Presently, traditional techniques to reduce mechanical stress migration rely on adding extra process steps in the fabrication process. For example, those well-known techniques for reducing void formation include improving via shape, via cleaning, barrier metal adhesion improvement, increasing copper grain size by annealing, and implementing dual vias to wide metal lines. However, virtually all of these techniques also require adding extra steps to the manufacturing process, thereby adding extra costs, complexity and time delays.

Thus, a need exists to provide an improved technique to reduce the migration of metal atoms in integrated circuits to improve reliability. In addition, a need exists to provide the technique to reduce mechanical stress migration preferably without having to add extra steps to the manufacturing process.

SUMMARY OF THE INVENTION

The problems outlined above are addressed in a large part by an apparatus and method for reducing failures caused by the migration of metal atoms in integrated circuits, as described herein. According to one form of the invention, a semiconductor device is prepared by an annealing process to interconnect at least two components of the device by a conductor line surrounded by an insulator material. The annealing process results in formation of residual mechanical stresses, which are typically tensile or compressive within the conductor line and the insulator material respectively. A notch is formed on a selective portion of the conductor line. The formation of the notch on the selective portion generates extra stress components within the conductor line. The position of the notch is selected so that the extra stress components substantially counteract the residual mechanical stresses, thereby causing a net reduction in the residual mechanical stresses to suppress the movement of metal atoms. The reduction in the residual stresses and suppression of movement of metal atoms results in a corresponding improvement in the reliability of the device.

According to another aspect of the invention, the method for reducing failures in a semiconductor circuit caused by residual mechanical stress includes placing a notch shape in a layout of a selective portion of a metal line mask for patterning a plurality of conductor lines included in the circuit. A portion of a semiconductor circuit is fabricated to include a conductor line surrounded by an insulator material. The conductor line electrically interconnects at least two components of the circuit. The fabrication of the portion of the semiconductor circuit results in formation of residual mechanical stresses within the conductor line and the insulator material due to a mismatch between coefficients of thermal expansion of the conductor line and the insulator. The circuit is generally prepared by an annealing process, which produces thermal stresses as a result of the mismatch between coefficients of thermal expansion and the thermal stresses generate the

5

residual stresses. One or more notches are designed on a selective portion of the conductor line. The formation or positioning of the notch on the selective portion generates extra stress components within the conductor line. The extra stress components generated by the notch substantially counteract the residual stresses to suppress movement of metal atoms. This reduces the movement of metal atoms thereby causing the reduction of mechanical stress induced voids within the semiconductor circuit.

Several advantages are achieved by the method and system according to the illustrative embodiments described herein. The embodiments advantageously provide for a system and method for reducing failures in a semiconductor circuit caused by migration of metal atoms. The extra stress components generated by the notching technique advantageously reduce the mechanical residual stress and improve reliability without having to add extra steps to the manufacturing process thereby avoiding addition of extra costs, complexity and time delays.

Other forms, as well as objects and advantages of the invention will become apparent upon reading the following detailed description and upon reference to the accompanying drawings.

BRIEF DESCRIPTION OF THE DRAWING

Novel features believed characteristic of the invention are set forth in the appended claims. The invention itself, however, as well as a preferred mode of use, various objectives and advantages thereof, will best be understood by reference to the following detailed description of an illustrative embodiment when read in conjunction with the accompanying drawings. Elements, which appear in more than one figure herein, are numbered alike in the various figures.

FIGS. 1A, 1B, 1C and 1D are illustrative diagrams of an interconnect structure of IC with multi-level of interconnection, described herein above, according to prior art.

FIG. 2A is an illustrative schematic diagram for generating extra mechanical stress components in a conductor line, according to an embodiment.

FIG. 2B is a schematic diagram to illustrate effects of varying angle alpha of FIG. 2A on the extra mechanical stress components, according to an embodiment.

FIGS. 2C-2H are illustrative schematic diagrams for generating extra mechanical stress components by forming various notches in a conductor line, according to an embodiment.

FIGS. 3A1 and 3A2 are illustrative schematic diagrams for optimally positioning one or more notches of FIGS. 2A-2H to reduce mechanical stress induced voiding (SIV) in metal interconnects, according to an embodiment.

FIGS. 3B, 3C and 3D are illustrative schematic diagrams of a multilayer semiconductor device having mechanical stress induced void formation prior to generating extra mechanical stress components.

FIG. 3E is an exemplary cross-sectional view similar to view section AA-AA of FIG. 3d of a multi-layer semiconductor device with reduced mechanical stress induced void formation, according to an embodiment.

FIG. 3F is an exemplary cross-sectional view (similar to view section AA-AA of FIG. 3d) of a multi-layer semiconductor device with reduced stress induced void formation, according to an embodiment.

FIG. 4 illustrates forming notches of various shapes to reduce mechanical stress induced voiding (SIV) in metal interconnects, according to an embodiment.

6

FIG. 5 is a flow chart illustrating a method for reducing failures in a semiconductor circuit, according to an embodiment.

DETAILED DESCRIPTION

While the invention is susceptible to various modifications and alternative forms, specific embodiments thereof are shown by way of example in the drawings and will be described herein in detail. It should be understood, however, that the drawings and detailed description thereto are not intended to limit the invention to the particular form disclosed, but on the contrary, the intention is to cover all modifications, equivalents and alternatives falling within the spirit and scope of the present invention as defined by the appended claims.

Traditional mechanical stress induced void reduction techniques used in semiconductor devices made from copper and low dielectric insulator have relied on adding extra steps to the manufacturing process. Hence, virtually all of these techniques also add extra costs, complexity and time delays. The present invention describes an apparatus and method for an improved semiconductor device having reduced stress induced void formations. According to one form of the invention, a semiconductor device is prepared by an annealing process to interconnect at least two components of the device by a conductor line surrounded by an insulator material. The annealing process results in formation of residual mechanical stresses, which may be tensile or compressive within the conductor line and the insulator material. A notch is formed on a selective portion of the conductor line. The formation of the notch on the selective portion generates extra stress components within the conductor line. The position of the notch is selected so that the extra stress components substantially counteract the residual mechanical stresses, thereby causing a net reduction in the residual stresses. The net reduction in residual mechanical stresses reduces movement of metal atoms. The reduction in the residual mechanical stresses and suppression of movement of metal atoms results in a corresponding improvement in the reliability of the device.

FIG. 2A is an illustrative schematic diagram for generating extra mechanical stress components in a conductor line, according to an embodiment. A conductor line 210 extending in an X-Y direction (or alternatively the top view) is shown. In one embodiment, the conductor line 210 is fabricated from a metal such as copper or an alloy of copper. In one embodiment, the conductor line 210 includes one of metal lines 110, 115, 117 and 120. A notch 220 is intentionally formed on a selective portion 230 of the conductor line 210. The notch 220 may be formed by simply using the same mask for patterning the conductor line 210. That is, the edge of the selective metal line portion 230 is not a straight line but a notch shape. The notch 220 may be formed in a variety of possible shapes including regular polygons and irregular polygons. In the depicted embodiment, the shape of the notch 220 substantially resembles a trapezoid.

In the depicted embodiment, the extra mechanical stress components 250 include the tensile mechanical stress component 252 in the Y direction and the compressive stress component 254 in the X direction. The magnitude of the extra mechanical stress components 250 is related to an angle alpha (a) 260 and an area associated with the notch 220, which is defined in FIG. 2A by the area of the trapezoid.

Further details of the effects of varying angle alpha 260 on the extra stress components 250 are shown in FIG. 2B.

Still referring to FIG. 2A, the magnitude of the extra mechanical stress components 250 gradually decreases at

areas away from the notch **220**. That is, the magnitude of the extra stress components **250** is the strongest immediately surrounding the notch **220**. The extra stress components **250** gradually decrease towards the center of the conductor line **210** and are even lower for areas located on the opposite edge of the conductor line **210**. Additional details of the distribution characteristics of the extra stress components **250** generated within the conductor line **210** by the formation of notches having various sizes and shapes are shown in FIGS. 2C-2H.

Still referring to FIG. 2A, and as described earlier the conductor line **210**, which is typically used to interconnect two or more components of an IC (not shown), has residual mechanical stresses (not shown) caused by residual thermal stresses (not shown) generated during the manufacturing process of the IC. The total, net or resultant mechanical stress effect within the conductor line **210** is a super-position of the extra mechanical stress components **250** generated by the notch **220** and the residual mechanical stresses which are normally present within the conductor line **210** before the formation of the notch **220**. Further details of circuit layout techniques for forming one or more notches on the conductor line **210** to generate extra mechanical stress components **250** that substantially counteract the residual mechanical stresses are shown in FIG. 3.

FIG. 2B is a schematic diagram to illustrate effects of varying angle alpha of FIG. 2A on the extra mechanical stress components, according to an embodiment. In the depicted embodiment, when the angle alpha **260** is greater than 45 degrees then the ratio of the extra compressive component **254** in the X direction to the extra tensile component **252** in the Y direction is greater than one at any point adjacent to the notch **220**. That is, the extra mechanical stress components **250** are largely compressive when the angle alpha **260** is greater than 45 degrees. Conversely, when the angle alpha **260** is less than 45 degrees then the ratio of the extra compressive component **254** in the X direction to the extra tensile component **252** in the Y direction is less than one at any point adjacent to the notch **220**. That is, the extra mechanical stress components **250** are largely tensile when the angle alpha **260** is less than 45 degrees.

FIGS. 2C-2H are illustrative schematic diagrams for generating extra mechanical stress components by forming various notches in a conductor line, according to an embodiment. Referring to FIG. 2C, two substantially similar notches **220** and **222** in the shape of a trapezoid are symmetrically formed on opposite edges **240** and **242** respectively of the conductor line **210**. In the depicted embodiment, the formation of symmetrically placed notches **220** and **222** generate extra mechanical stress components **250**, which are more symmetric and uniformly distributed in the center zone of the conductor line **210**.

Referring to FIG. 2D, two substantially similar notches **270** and **272** in the shape of a triangle are asymmetrically formed on opposite edges **240** and **242** respectively of the conductor line **210**, according to an embodiment. In the depicted embodiment, the formation of asymmetrically placed notches **270** and **272** generate extra mechanical stress components **250**, which are more asymmetrically distributed in the center zone of the conductor line **210** but uniformly distributed along a center line joining the two notches **270** and **272**.

Referring to FIG. 2E, two substantially similar notches **274** and **276** in the shape of a rectangle are symmetrically formed on opposite edges **240** and **242** respectively of the conductor line **210**, according to an embodiment. In the depicted embodiment, the formation of symmetrically placed notches

274 and **276** generate extra mechanical stress components **250**, which are more symmetrically and uniformly distributed in the center zone of the conductor line **210**.

Referring to FIG. 2F, two substantially similar notches **280** and **282** in the shape of an arc are symmetrically formed on opposite edges **240** and **242** respectively of the conductor line **210**, according to an embodiment. In the depicted embodiment, the formation of symmetrically placed notches **280** and **282** generate extra mechanical stress components **250**, which are more symmetrically and uniformly distributed in the center zone of the conductor line **210**.

Referring to FIG. 2G, two notches **284** and **286** both in the shape of a trapezoid but having dissimilar sizes are symmetrically formed on opposite edges **240** and **242** respectively of the conductor line **210**, according to an embodiment. In the depicted embodiment, the formation of dissimilar sized notches **270** and **272** generate extra mechanical stress components **250**, which are more asymmetrical along a center line joining the two notches **284** and **286**.

Referring to FIG. 2H, two dissimilar notches **290** and **292** in the shape of an arc and a trapezoid respectively are symmetrically formed on opposite edges **240** and **242** respectively of the conductor line **210**, according to an embodiment. In the depicted embodiment, the formation of dissimilar shaped notches **270** and **272** generate extra mechanical stress components **250**, which are more asymmetrical along a center line joining the two notches **290** and **292**.

Other variations in the size and shape of the notch **220** are contemplated. It will be apparent to those of skill in the art that numerous changes may be made in such details without departing from the spirit and scope of the present invention.

FIGS. 3A1 and 3A2 illustrative schematic diagrams for optimally positioning one or more notches of FIGS. 2A-2H to reduce mechanical stress induced voiding (SIV) in metal interconnects, according to an embodiment. As described earlier, void formation **160** (generally associated with tensile stresses in metal line) is related to the movement of metal atoms (e.g., copper atoms) away from via in a multi-layer circuit. Referring to FIG. 3A1, in a multi-layer semiconductor device (not shown), the conductor line **210** is under residual tensile mechanical stress and includes via **240** to interconnect to another layer (not shown) in the device. Presence of residual mechanical tensile stress is related to the movement of copper atoms away from via **240**. In one embodiment, via **240** is same as via **130**. In order to suppress movement of copper atoms away from via **240**, extra mechanical stress components **250** are generated or introduced around the via **240** position within the conductor line **210** that substantially counteract the residual tensile mechanical stresses. That is, notches **320** and **330** are optimally positioned or formed on edges **322** and **332** of the conductor line **210** thereby generating extra mechanical stress components **250** that are biaxial and substantially counteract the residual mechanical stresses. Selecting the angle alpha **260**, which is greater than 45 degrees for each of the notches **320** and **330**, generates extra bi-axial compressive stresses around via **240**. The extra stress components **250** thus suppress or substantially reduce the movement of copper atoms away from via **240**. In one embodiment, extra mechanical stress components **250** are generated to suppress accumulation (or hillock growth) (not shown) that is generally associated with compressive residual mechanical stresses. The extra stress components **250** generated by the notching thus advantageously reduce the residual stress without having to add extra steps to the manufacturing process.

Referring to FIG. 3A2, optimal positioning of three notches to reduce mechanical stress induced voiding (SIV) in

metal interconnects is illustrated, according to an embodiment. In the depicted embodiment, three notches **390**, **392** and **394** are formed to generate extra stress components **250** around the two vias **310** and **311**. In one embodiment, vias **310** and **311** are same as vias **130** and **140**.

FIGS. **3B**, **3C** and **3D** illustrate schematic diagrams of a multi-layer semiconductor device having mechanical stress induced void formation prior to generating extra mechanical stress components and FIGS. **3E** and **3F** illustrate exemplary cross-sectional views of a multi-layer semiconductor device with reduced mechanical stress induced void formation after generating extra mechanical stress components, according to an embodiment. Referring to FIG. **3B**, a top view of a multi-layer semiconductor device **300** is shown, according to an embodiment. Included in the device **300** is an upper metal line **340** connected to a lower metal line **350** by via **310**. The upper metal line **340** is wider in comparison to the lower metal line **350**. In one embodiment, the upper metal line **340** is connected to component **342** included in the device **300** and the lower metal line **350** is connected to component **352** also included in the device **300**. Examples of various components such as **342** and **352** interconnected by conductors within an IC may include transistors, diodes, resistors, capacitors, contact terminals and the like.

Referring to FIG. **3C**, an isometric view of the multi-layer semiconductor device **300** is shown, according to an embodiment. The upper metal line **340** connected to the lower metal line **350** by via **310**. The upper metal line **340** is wider in comparison to the lower metal line **350**. In one embodiment, the upper metal line **340** is connected to component **342** included in the device **300** and the lower metal line **350** is connected to component **352** also included in the device **300**.

Referring to FIG. **3D**, a cross-sectional view AA-AA of the multi-layer semiconductor device **300** of FIG. **3C** is shown, according to an embodiment. In the depicted embodiment, via **310** is insulated by a thin barrier metal layer (e.g. Tantalum nitride (TaN)) **312**. The mechanical stress induced void formation **360**, which is substantially same as the void **160**, is formed by the migrating of copper atoms away from via **310**. That is, in direction **314** toward the upper wider metal line **340**. The lower metal line **350** is insulated by a low k dielectric **351**.

Referring to FIG. **3E**, an exemplary cross-sectional view (similar to view AA-AA of FIG. **3D**) of a multi-layer semiconductor device **301** with reduced stress induced void formation after generating extra mechanical stress components is shown, according to an embodiment. In the depicted embodiment, via **310** is insulated by the

TaN barrier **312**. In this embodiment, forming notches (not shown) in the upper metal line **340** (similar to the notches **320** and **330** illustrated in FIG. **3A**) generates extra compressive stress components **360**. The direction of the extra compressive stress components **315** is substantially opposite to that of the residual mechanical stress e.g., in direction **314** toward the upper metal line **340** of FIG. **3D**, thereby suppressing the size of a stress induced void formation **362**. The stress induced void formation **362** is reduced in comparison to the stress induced void formation **360** of FIG. **3D**. In the depicted embodiment, the lower metal line **350** is insulated by the low k dielectric **351**.

Referring to FIG. **3F**, an exemplary cross-sectional view similar to view AA-AA of FIG. **3D** of a multi-layer semiconductor device **302** with reduced stress induced void formation after generating extra mechanical stress components is shown, according to an embodiment. In the depicted embodiment, the lower metal line **350** is wider than the upper metal line **340**, and coupled by via **310**. The via **310** is insulated by

the TaN barrier **312**. In this embodiment, forming notches (not shown) in the lower metal line **350** similar to the notches **320** and **330** illustrated in FIG. **3A** generates extra compressive stress components. The direction **315** of the extra compressive stress components **250** is substantially opposite to that of the residual stress (caused by copper vacancies moving toward via **310** bottom), thereby suppressing the size of the reduced stress induced void formation **362**. The stress induced void formation **362** is thus reduced in comparison to the stress induced void formation **360** of FIG. **3D**. The lower metal line **350** is insulated by a low k dielectric **351**. The extra stress components **250** generated by notching technique thus advantageously reduce the residual mechanical stress without having to add extra steps to the manufacturing process.

Referring to FIG. **4**, forming notches of various shapes to reduce mechanical stress induced voiding (SIV) in metal interconnects is illustrated, according to an embodiment. Layout techniques for the formation of one or more notches may be applied on narrow conductor line **210** carrying a high current density at the cathode and anode sides. Inward notches **410** and **420**, similar to the notches **220** and **222**, are formed on adjacent edges **412** and **422** of the conductor line **210**. The conductor line **210** is connected to other components by vias **310** and **311**. In the depicted embodiment, formation of inwardly notching notches **410** and **420** generate extra mechanical stress components **250**, which are more symmetric and uniformly distributed around the via **310**. Thus, inward notching on cathode side generates the extra mechanical stress components **250**, which are compressive. The compressive extra stress components **250** generated, thereby, suppress copper atom movement away from via **310** (by electron flow). Similarly, outward notches **430** and **440** are formed on adjacent edges **412** and **424** of the conductor line **210**. In the depicted embodiment, formation of outwardly notching notches **430** and **440** on anode side generate tensile extra stress components **450**, which are more symmetric and uniformly distributed around the via **311**. Thus, the tensile extra stress components **450** suppress metal atom accumulation at anode area. That is, these components **450** suppress copper atom moving forward toward via **311** (by electron flow).

FIG. **5** is a flow chart illustrating a method for reducing failures in a semiconductor circuit, according to an embodiment. In step **510**, a notch shape is placed in a layout of a selective portion of a metal line mask for patterning a plurality of conductor lines included in the circuit. In step **520**, a portion of the circuit is fabricated to include the conductor line **210** having the notch shape. The conductor line **210** is surrounded by an insulator material interconnects at least two components of the circuit. The fabrication of this portion results in formation of residual stresses within the conductor line **210** and the surrounding insulator material. In step **530**, remaining portions of the circuit are fabricated to complete the circuit. The notch shape generates extra stress components within the conductor line **210** compared to forming the conductor line **210** without the notch shape. The extra stress components substantially counteract the residual stresses, thereby causing a net reduction in the residual stresses.

The description of the present embodiments have been presented for purposes of illustration, but are not intended to be exhaustive or to limit the invention to the forms disclosed. Many additional aspects, modifications and variations are also contemplated and are intended to be encompassed within the scope of the following claims. For example, the layout techniques are applicable to reduce residual stress as commonly encountered in modern copper interconnect and low k dielectric. If residual stress in copper line is compressive

11

(e.g., due to new low k dielectric materials with larger thermal expansion coefficients than copper or due to thermal treatment of copper) then the polarity of notching of the above layout techniques needs to be reversed. That is, outward notching for extra compressive components and inward notching for extra tensile components. As another example, notches may be formed within a wide metal line in addition to the edges of the conductor line for generating extra bi-axial compressive components around via areas. While certain aspects of the present invention have been described in the context of a copper line, those of ordinary skill in the art will appreciate that the processes of the present invention are capable of being applied to any metal lines in a variety of forms.

Although the embodiments above have been described in considerable detail, numerous variations and modifications will become apparent to those skilled in the art once the above disclosure is fully appreciated. It is intended that the following claims be interpreted to embrace all such variations and modifications.

What is claimed is:

1. A method comprising: providing a mask including a plurality of mask lines including at least a first mask line including at least one notch shape;

fabricating a portion of a semiconductor circuit using the mask to form a plurality of conductive lines corresponding to the plurality of mask lines and including a first conductive line corresponding to the first mask line, the first conductive line including parallel edges extending in a lengthwise direction and having at least a first notch positioned at a first lengthwise location and a second notch positioned at a second lengthwise location that is different from the first lengthwise location on a first edge of said parallel edges, each of the first and second notches corresponding to a respective notch shape of the at least one notch shape, wherein the first conductive line is surrounded by an insulator material and interconnects at least two components of the semiconductor circuit and the fabricating results in formation of residual stresses within the plurality of conductive lines and the insulator material; and

further fabricating further portions of the semiconductor circuit to produce the semiconductor circuit including to the first conductive line at the first lengthwise location between a first edge of the parallel edges and an innermost edge of the first notch and is aligned with the second notch in a widthwise direction,

wherein the first and the second notch extend from the first edge of the first conductor line and a second parallel edge of said first conductor line is a substantially straight line that extends continuously between said first and second lengthwise locations,

wherein each of the at least one first notch and the second notch generate extra stress components within the first conductive line compared to other conductive lines of the plurality of conductive lines and wherein the extra stress components substantially counteract the residual stresses.

2. The method of claim 1, wherein each the first notch is an inwardly extending notch and the extra stress components generated by the inwardly extending notch are compressive in an area adjacent to the inwardly extending notch.

3. The method of claim 1, wherein the second notch is an outwardly extending notch and the extra stress components generated by the outwardly extending notch are tensile in an area adjacent to the outwardly extending notch.

12

4. The method of claim 1, wherein the fabricating includes an annealing process that produces the residual stresses due to thermal stresses that create a mismatch between coefficients of thermal expansion of the plurality of conductive lines and the insulator material.

5. A method for forming a semiconductor device, the method comprising: fabricating a portion of the semiconductor device using a mask to form a plurality of conductive lines corresponding to a plurality of mask lines and including a first conductive line corresponding to a first mask line including at least one notch shape, the first conductive line including parallel edges connecting at least two components;

forming an inward extending notch on a first edge of the parallel edges and extending inwardly from the first edge at a first lengthwise location along a length of the first conductor line;

forming an outward extending notch on the first edge and extending outwardly from the first edge at a second lengthwise location along the first conductor line and spaced apart from the first lengthwise location, a second edge of the parallel edges being a continuous straight line extending from the first lengthwise location to the second lengthwise location, and at least one further notch disposed on an adjacent non-parallel edge of said first conductor line;

forming a via and coupling the first conductor line at the first lengthwise location, the via spaced apart from the inward extending notch, and disposed completely between the inward extending notch and the second edge at the first lengthwise location; and

forming a further via between the outward extending notch and the second edge at the second lengthwise location.

6. The method as in claim 5, further comprising disposing insulator materials surrounding the first conductor line.

7. The method as in claim 5, wherein the forming a first conductive line connecting at least two components includes annealing.

8. The method as in claim 5, wherein each of the forming an inward extending notch and forming an outward extending notch comprise forming a notch with a polygon shape.

9. The method as in claim 5, wherein the forming an inward extending notch comprises forming the inward extending notch having an edge that intersects the first edge at an angle less than about 135 degrees.

10. The method as in claim 5, wherein the forming a first conductor line connecting at least two components includes annealing and at least one of the forming an inward extending notch or the forming an outward extending notch generates stress components that counteract residual stresses formed by the annealing.

11. A method for forming a semiconductor device, the method comprising:

fabricating a portion of the semiconductor device using a mask to form a plurality of conductive lines corresponding to a plurality of mask lines and including a first conductive line corresponding to a first mask line including at least one notch shape, the first conductive line including parallel edges connecting at least two components;

forming an inward extending notch on a first edge of the parallel edges and extending inwardly from the first edge at a first lengthwise location along a length of the first conductor line;

forming an outward extending notch on the first edge and extending outwardly from the first edge at a second lengthwise location along the first conductor line and spaced apart from the first lengthwise location, wherein

13**14**

a second edge of the parallel edges is a straight line that extends continuously between the first and second lengthwise locations;
forming at least one further notch on an adjacent non-parallel edge of the first conductor line;
forming first and second vias, the first via disposed adjacent to the inward extending notch at the first lengthwise location and the second via disposed inwardly adjacent to the outward extending notch at the second lengthwise location; and
disposing insulator material substantially surrounding the first conductor line.

12. The method as in claim **11**, wherein the forming at least one further notch comprises forming a second inward extending notch.

13. The method as in claim **11**, wherein the forming a first conductor line connecting at least two components includes annealing, and the annealing results in formation of residual stresses and at least one of the inward extending notch, the outward extending notch or the at least one further notch, produces stresses that counteract the residual stresses.

* * * * *